

Investigating Navigation Strategies In Virtual Worlds: A GOMS Analysis

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ABSTRACT

A conclusion drawn in the study of navigation and orientation in virtual spaces [4, 5] stated that the differences in behavior observed between treatments was far greater than the differences observed between individual subjects thus indicating that generalizations can be drawn on user behavior and strategy on performance of navigation tasks in virtual spaces based on the types of cues or tools made available. This report will describe a detailed analysis of cognitive activity observed during performance of navigation tasks in these virtual spaces in an effort to verify or falsify this statement. A comprehensive task analysis will be presented for each treatment in the study.

KEYWORDS:

Navigation, Orientation, Virtual Worlds, Cognitive Maps, GOMS Analysis, Task Analysis

INTRODUCTION

This report describes a complete task analysis of the study on navigation and orientation in virtual spaces detailed in [4, 5]. The introductory study displayed a number of promising avenues of research. It suggested that a relationship exists between the tools and cues displayed in the virtual world, and the behaviors and strategies employed by users for performance of navigation tasks. However, the analysis was too shallow to verify this statement. The objective of this report will be to perform an in-depth evaluation detailing cognitive activity of users in these spaces and to draw conclusions as to whether or not the observed differences can be attributed to the cues and tools or simply to differences in individual users.

The type of analysis used here was developed initially for use with desktop-style interfaces in which parallelism between subtasks is minimal. A challenge in this evaluation will be to manage the sometimes heavy parallelism between subtasks often observed in virtual world applications.

The Effectiveness of Navy Electronic Warfare Systems (ENEWS) Program in the Tactical Electronic Warfare Division at the Naval Research Laboratory has been studying the application of virtual environment technology to naval simulations since 1991. ENEWS is involved with the simulation and visualization of all aspects of the electromagnetic environment. With all its complexity, immersive visualizations of this environment add the burden of maintaining large spaces to the already arduous tasks of the operator. This is quickly realized when users of these applications become disoriented immediately upon entering the virtual space [1]. Thus the objective of this research was to generalize the problem and find solutions which match the operator's expectations based on physical world analogies enabling a simplification of navigation tasks.

THE STUDY

The world chosen for this initial study was designed to be similar to a physical environment. The world consisted of a large rectangular grid plane which was randomly filled with a varying number of simple ship models. The subject's initial position in the world is also randomly chosen and is marked with a polygon on the grid plane. Figure 1 shows a schematic illustration of the virtual world.

The study included nine subjects, seven male and two female all of whom have a technical background and are experienced computer users. Only three of the subjects had any experience using the apparatus and none had any previous knowledge of the subject matter of the study.

A Fake Space Labs, Inc. BOOM2C device was used with a monochromatic display and mechanical tracking of the viewpoint. The spatial audio cue was implemented with the Audio Cube by Visual Synthesis, Inc. which uses a cube of eight external speakers to position a sound sample.

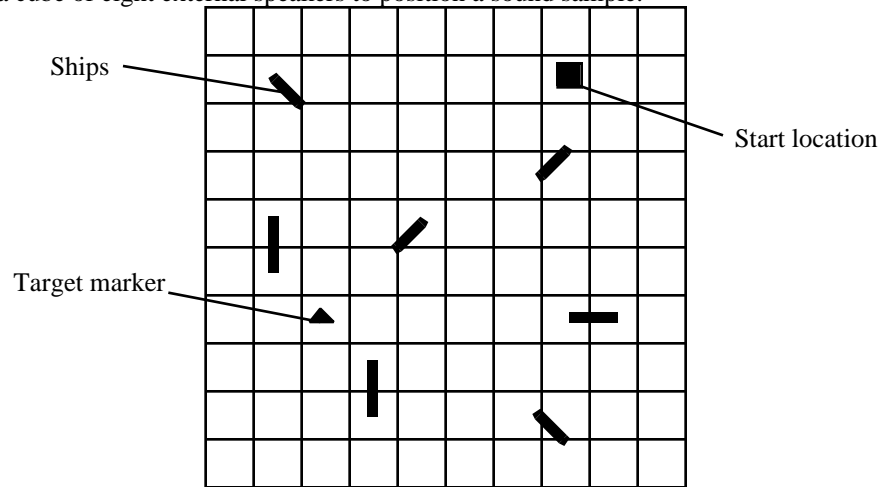


Figure 1: Schematic diagram of the virtual world.

Procedure

Since the focus of this study is on the relationship between human navigation behavior to spatial cues and tools, three different forms of search were investigated:

- Exploration: The primary goal is to gain familiarity with the environment.
- Naïve search: The subject is searching for an object of which its appearance but not its location is known.
- Informed search: The subject has some knowledge about the location of the object.

For each trial, a large, finite world was randomly configured based on the number of objects required (sparse or dense world) and the tools or cues to be made available. The relative size of the largest objects and landmarks to the world was approximately 1:100. Objects in the space were identical simple ship models. The target object was a small pyramid. Movement was initiated by a button press on the BOOM2C. Both forward and backward movement of constant velocity and in the direction of view were allowed.

Before initial participation, subjects were informed as to the nature of the study and what they would be seeing in the world. Before each treatment, subjects were given information about the structure or representation of the tool to be used but were never prompted with suggested strategies. The task was described to the subjects as having three primary parts:

1. Move through the space at will trying to view as much space as possible. (Exploration)
2. Search for the target object. (Naïve search)
3. On cue, return to the start position. (Informed search)

Each subject was instructed to browse the space in an investigative fashion. Spatial knowledge gathered in this step is useful in the subsequent search tasks. At some random time before the target was visible to the subject, each was told to search for the target object. After moving sufficiently close to the target, an audible bell would sound signalling the subject to return to the initial position (marked by a square). During each trial, subjects were asked to freely describe choices being made, strategies, and general actions.

Subject behavior was recorded in written notes documenting observations made by the evaluator and comments made by the subjects during and after each trial. Of particular interest was data on positional or orientational information being gleaned from the environment or the tools and strategies used to accomplish any part of the task. Each scenario of tool(s) and world type was tried by different subjects until a generalization could be made on behavior in that scenario. Typically, five to six trials per scenario were used.

Results

The results of the study will be presented here in the form of a GOMS analysis. This style of task analysis was introduced by Card, Moran, and Newell [3] in 1983 and has been widely used as a form of detailed evaluation of tasks involving complex cognitive actions [6, 8, 9]. In the GOMS model, a user's cognitive structure is described in terms of a set of Goals, a set of Operators, a set of Methods for achieving the goals, and a set of Selection rules for choosing among competing methods for goals. It is assumed that behavior consists of the serial execution of operators. Also, a level of granularity must be chosen before the analysis can begin so that the results are not too vague or too detailed. The finer the grain of the analysis, the closer it will be to describing direct cognitive activity. This analysis has been done at the functional level in order to make qualitative predictions about behaviors. This is of coarser grain than the keystroke and argument levels which will model an action in lexical units but is finer grain than the unit-task level which typically is a high level description of the entire task.

The general task can be described in the GOMS model as the following:

GOAL: VIRTUAL-SPACE-WALKTHROUGH

- . GOAL: LEARN-SPACE
- . GOAL: SEARCH-TARGET
- . GOAL: SEARCH-HOME.

entire task
learning subtask
naive search subtask
informed search subtask

The three subgoals to GOAL:VIRTUAL-SPACE-WALKTHROUGH, are all performed sequentially and in the specified order. The notation generalizes to represent sequential goals. However, in this study, subtasks are often performed in parallel. Exceptions to the sequentialism of the notation are usually (but not always) the result of the following parallelism (Figure 2) illustrated in this PERT chart [10]. A PERT chart (Program Evaluation Revision Technique) is a network of tasks and subtasks used to evaluate dependencies. It is read left to right in time with links representing dependencies.

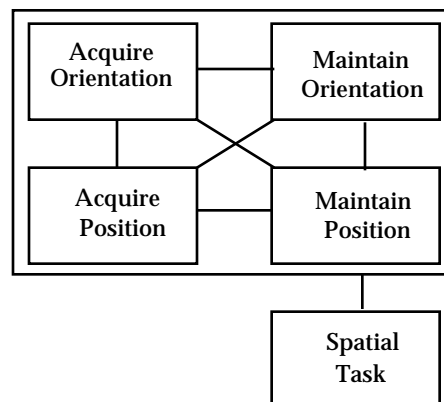


Figure 2: PERT chart of generalized parallelism

The subtasks of acquiring orientation and position often occur in parallel and are prerequisites for the subtasks of maintaining orientation and position. These tasks can be grouped together and treated as a single task which occurs in parallel with some generic spatial task. This network of activities is recurrent in many spatial tasks and will be referenced within the analysis below as grouped subtasks within a goal. The following section will describe the detailed analysis of these subgoals as observed in different trials in the study. These observations are meant to be a generalization of behaviors across the majority of the subjects.

Landmarks

The synthetic landmarks placed in the world are distinct from other objects in the space and are placed randomly when the environment is created. The landmarks used were simple rectangular columns, but they were considerably larger than the ships. See figure 3.

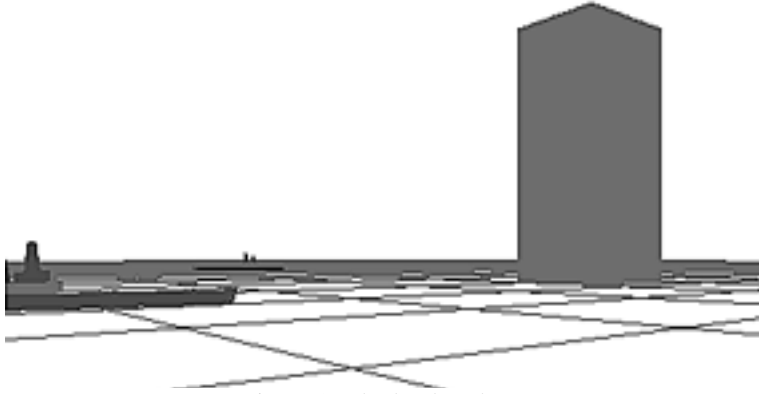


Figure 3: The landmark cue

GOAL: ACQUIRE-ORIENTATION

. select [USE-LANDMARK-METHOD
.
 USE-OBJECT-METHOD
.
 USE-COMBINATION-METHOD].

*if available, get directional
information from landmarks
else if available, get directional
information from objects
else if available, get directional
information from combinations of
landmarks and objects*

GOAL: ACQUIRE-POSITION

. select [USE-LANDMARK-METHOD
.
 USE-OBJECT-METHOD
.
 USE-COMBINATION-METHOD].

*if available, get directional and
distance information from
landmarks
else if available, get directional and
distance information from objects
else if available, get directional and
distance information from
combinations of landmarks and
objects*

GOAL: LEARN-SPACE

GOAL: ACQUIRE-ORIENTATION
GOAL: ACQUIRE-POSITION
GOAL: MAINTAIN-ORIENTATION-INFO
GOAL: MAINTAIN-POSITION-INFO
MOVE. *general movement noting relative*

learning subtask

*repeat throughout task performance
repeat throughout task performance*

positions of objects and landmarks

GOAL: SEARCH-TARGET

GOAL: MAINTAIN-ORIENTATION-INFO
GOAL: MAINTAIN-POSITION-INFO
select [USE-EXHAUSTIVE-METHOD
.
 USE-PARTITION-METHOD].

*naive search subtask
repeat throughout task performance
repeat throughout task performance
if space is not conceptually
partitioned, perform an organized,
exhaustive search
else, search partitioned areas
systematically*

GOAL: SEARCH-HOME *informed search subtask*

. select [USE-EXHAUSTIVE-METHOD

 USE-DIRECT-METHOD].

*if orientation and position
information has not been adequately
maintained, perform an organized,
exhaustive search
else, move in direction of home
until visual contact is made*

GOAL: MAINTAIN-ORIENTATION-INFO
 PATTERN-ALIGNMENT.

*align viewpoint with directional
configuration(s) from
GOAL:ACQUIRE-ORIENTATION*

GOAL: MAINTAIN-POSITION-INFO
 PARTITION-SPACE.

*partition space using directional
configuration(s) from
GOAL:ACQUIRE-ORIENTATION*

GOAL: REACQUIRE-ORIENTATION
 MOVE-TO-FAMILIAR-LOCATION

. select [USE-LANDMARK-METHOD

 USE-OBJECT-METHOD
 USE-COMBINATION-METHOD].

*if orientation is lost
search for and move back to any
directional configuration used in the
GOAL:ACQUIRE-ORIENTATION
same as in
GOAL:ACQUIRE-ORIENTATION*

GOAL: REACQUIRE-POSITION
 MOVE-TO-FAMILIAR-LOCATION

. select [USE-LANDMARK-METHOD

 USE-OBJECT-METHOD
 USE-COMBINATION-METHOD].

*if position information is lost
search for and move back to any
directional configuration used in the
GOAL:ACQUIRE-POSITION
same as in
GOAL:ACQUIRE-POSITION*

Reacquisition of position and orientation information was not performed regularly but when required, it demanded extensive time to relocate familiar space.

Cartesian Coordinate Tool

This coordinate feedback system displays a continuous textual readout of Cartesian coordinates of the subject's current position. This is similar to the type of information available from the global position indicator. The origin is the center of the world with elevation zero being the ground plane. See figure 4.

GOAL: ACQUIRE-ORIENTATION
 select [MOVE-ALONG-GRID

 ESTABLISH-QUADRANTS

 COMBINATION].

*align movement with grid line
observing change in coordinates
changes in coordinate sign specifies
quadrants
obtain information both from the
grid and from quadrants*

GOAL: ACQUIRE-POSITION
 TEXTUAL-FEEDBACK.

*current position given explicitly in
text*

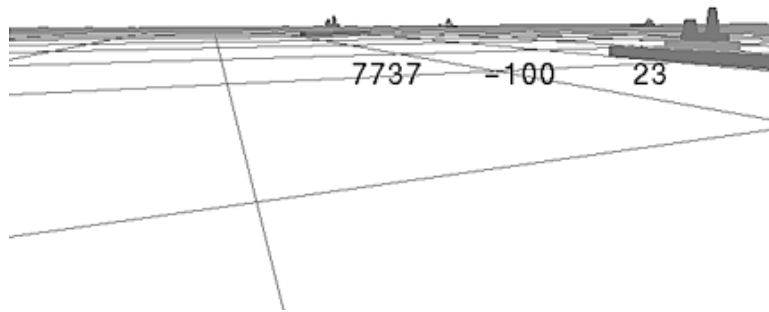


Figure 4: The Cartesian coordinate tool

GOAL: LEARN-SPACE	<i>learning subtask</i>
. GOAL: ACQUIRE-POSITION	<i>must be remembered for return to home</i>
. GOAL: ACQUIRE-ORIENTATION	
GOAL: MAINTAIN-ORIENTATION-INFO	<i>repeat throughout task performance</i>
GOAL: MAINTAIN-POSITION-INFO	<i>repeat throughout task performance</i>
MOVE. <i>general movement noting quadrants</i>	<i>and positions of objects</i>
GOAL: SEARCH-TARGET	<i>naive search subtask</i>
GOAL: MAINTAIN-ORIENTATION-INFO	<i>repeat throughout task performance</i>
GOAL: MAINTAIN-POSITION-INFO	<i>repeat throughout task performance</i>
select [USE-EXHAUSTIVE-METHOD	<i>if orientation and quadrant information is not preserved, perform an organized, exhaustive search</i>
USE-PARTITION-METHOD].	<i>else, search quadrants systematically</i>
GOAL: SEARCH-HOME <i>informed search subtask</i>	
. GOAL: REACQUIRE-POSITION	
. GOAL: REACQUIRE-ORIENTATION	
. USE-DIRECT-METHOD.	<i>move in direction of home until visual contact is made</i>
GOAL: MAINTAIN-ORIENTATION-INFO	
. GRIDLINE-ALIGNMENT.	<i>align movement with a gridline noting change in textual information</i>
GOAL: MAINTAIN-POSITION-INFO	
. TEXTUAL-FEEDBACK	<i>current position given explicitly in text</i>
. PARTITION-SPACE.	<i>partition space into quadrants using coordinate signs</i>
GOAL: REACQUIRE-ORIENTATION	<i>if orientation is lost</i>
. select [MOVE-ALONG-GRID	<i>align movement with grid line</i>

- . ESTABLISH-QUADRANTS
- . COMBINATION].

*observing change in coordinates
changes in coordinate sign specifies
quadrants
obtain information both from the
grid and from quadrants*

- GOAL: REACQUIRE-POSITION
- . TEXTUAL-FEEDBACK.

*if position information is lost
current position given explicitly in
text*

Reacquisition of position information was not performed at all because of its accessibility. However, reacquisition of orientation information was performed extensively and required time to make the necessary movements for its determination.

Polar Coordinate Tool

This coordinate feedback system displays a continuous textual readout of polar coordinates of the subject's current position. This is also similar to the type of information available from the global position indicator. The origin (range zero) is the center of the world with some arbitrary zero heading and with elevation zero being the ground plane. See figure 5.

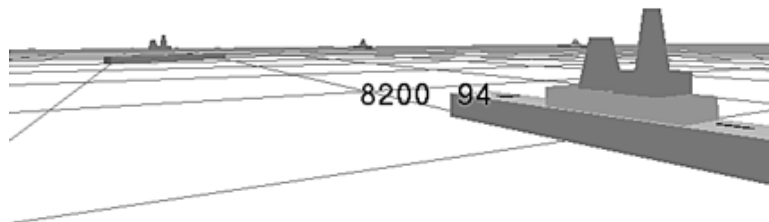


Figure 5: The polar (range/bearing) coordinate tool

- GOAL: ACQUIRE-ORIENTATION
- . MOVE-SWEEP. *sweeping movements noting*

changes in range and bearing

- GOAL: ACQUIRE-POSITION
- . TEXTUAL-FEEDBACK.

*current position given explicitly in
text*

- GOAL: LEARN-SPACE
- . GOAL: ACQUIRE-POSITION

*learning subtask
must be remembered for return to
home*

- . GOAL: ACQUIRE-ORIENTATION
- GOAL: MAINTAIN-ORIENTATION-INFO
- GOAL: MAINTAIN-POSITION-INFO
- MOVE. *general movement noting positions*

*repeat throughout task performance
repeat throughout task performance
of objects*

GOAL: SEARCH-TARGET

GOAL: MAINTAIN-ORIENTATION-INFO

GOAL: MAINTAIN-POSITION-INFO

USE-EXHAUSTIVE-METHOD.

naive search subtask

repeat throughout task performance

repeat throughout task performance

if orientation information is not

preserved, perform an organized,

exhaustive search

GOAL: SEARCH-HOME *informed search subtask*

. GOAL: REACQUIRE-POSITION

. GOAL: REACQUIRE-ORIENTATION

. USE-DIRECT-METHOD.

move in direction of home until

visual contact is made

GOAL: MAINTAIN-ORIENTATION-INFO

. MOVE-SWEEP. *sweeping movements noting*

changes in range and bearing

GOAL: MAINTAIN-POSITION-INFO

. TEXTUAL-FEEDBACK.

current position given explicitly in

text

GOAL: REACQUIRE-ORIENTATION

. MOVE-SWEEP. *sweeping movements noting*

if orientation is lost

changes in range and bearing

GOAL: REACQUIRE-POSITION

. TEXTUAL-FEEDBACK.

if position information is lost

current position given explicitly in

text

Reacquisition of position information was not performed at all because of its accessibility. However, reacquisition of orientation information was performed extensively and required time to make the necessary movements for its determination. This problem was compounded by the fact that the ground plane grid did not coincide with the coordinate system.

Districting

The world can be subdivided into districts. A set of visible lines are drawn in the world to divide it into smaller spaces. This is similar to showing political boundaries on a map, except that these are drawn in the world. See figure 6.

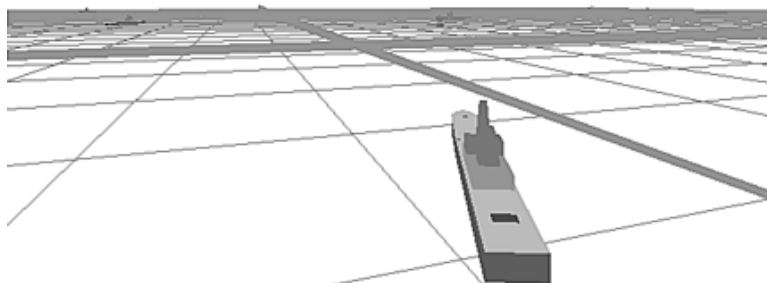


Figure 6: The district cue

GOAL: ACQUIRE-ORIENTATION . WITHIN-DISTRICT . DISTRICT-BORDERS.	<i>trivial task; district analogous to small world move along district borders noting spatial relationship to immediate neighbors</i>
GOAL: ACQUIRE-POSITION . WITHIN-DISTRICT . DISTRICT-BORDERS.	<i>trivial task; district analogous to small world move along district borders noting spatial relationship to immediate neighbors</i>
GOAL: LEARN-SPACE GOAL: ACQUIRE-ORIENTATION GOAL: ACQUIRE-POSITION GOAL: MAINTAIN-ORIENTATION-INFO GOAL: MAINTAIN-POSITION-INFO MOVE. <i>repeat until all district are visited;</i>	<i>learning subtask repeat throughout task performance repeat throughout task performance general movement within district noting relative positions of objects</i>
GOAL: SEARCH-TARGET GOAL: MAINTAIN-ORIENTATION-INFO GOAL: MAINTAIN-POSITION-INFO IN-DISTRICT-EXHAUSTIVE-SEARCH.	<i>naive search subtask repeat throughout task performance repeat throughout task performance repeat on successive districts until target is found</i>
GOAL: SEARCH-HOME <i>informed search subtask</i> . select [USE-EXHAUSTIVE-METHOD . USE-DIRECT-METHOD].	<i>if orientation and position information has not been adequately maintained, perform an organized, exhaustive search on each successive district until found else, move into home district and perform an exhaustive search until found</i>
GOAL: MAINTAIN-ORIENTATION-INFO . DISTRICT-ALIGNMENT.	<i>align viewpoint with the known orientation of connected districts</i>
GOAL: MAINTAIN-POSITION-INFO . PARTITION-SPACE.	<i>partition space using districts; position within district trivial</i>
GOAL: REACQUIRE-ORIENTATION . WITHIN-DISTRICT . select [MOVE-TO-FAMILIAR-LOCATION . BACKTRACK].	<i>if orientation is lost trivial task; district analogous to small world if district alignment is lost, move to neighboring districts until it becomes familiar; then restart task if district border connections are lost, backtrack within district to reestablish district orientation</i>

GOAL: REACQUIRE-POSITION
WITHIN-DISTRICT

. select [MOVE-TO-FAMILIAR-LOCATION

. BACKTRACK].

lost, backtrack within district to

*if position information is lost
trivial task; district analogous to
small world*

*if district alignment is lost, move
to neighboring districts until it
becomes familiar; then restart task
if district border connections are*

reestablish district orientation

Reacquisition of position and orientation information was not performed regularly but when required, its time demands were minimal due to the relatively small size of the districts.

Flying

For virtual worlds which are similar in dimension to the physical world, the ability to fly offers the same advantages to humans that it does to birds in the physical world. See figure 7.

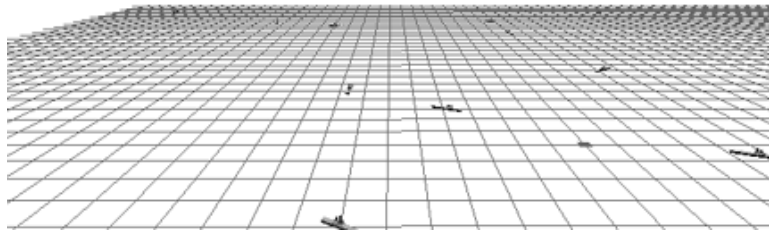


Figure 7: Sample view when flying motion is enabled

GOAL: ACQUIRE-ORIENTATION
INCREASE-ALTITUDE

OBSERVE-TOPOLOGY-ORGANIZATION.

*fly up to some altitude at which
necessary surface detail is visible
orientation gathered from
topological information of the
space and the organization of
objects in it*

GOAL: ACQUIRE-POSITION
INCREASE-ALTITUDE

OBSERVE-TOPOLOGY-ORGANIZATION.

*fly up to some altitude at which
necessary surface detail is visible
position information incomplete
because exact altitude is unknown;
2D position gathered from
topological information of the
space and the organization of
objects in it*

GOAL: LEARN-SPACE
GOAL: ACQUIRE-ORIENTATION
GOAL: ACQUIRE-POSITION

learning subtask

GOAL: MAINTAIN-ORIENTATION-INFO GOAL: MAINTAIN-POSITION-INFO MOVE.	<i>repeat throughout task performance repeat throughout task performance possibly varying altitude</i>
GOAL: SEARCH-TARGET GOAL: MAINTAIN-ORIENTATION-INFO GOAL: MAINTAIN-POSITION-INFO EXHAUSTIVE-SEARCH.	<i>naive search subtask repeat throughout task performance repeat throughout task performance maintaining an altitude at which the target can be seen, exhaustively search the space until found</i>
GOAL: SEARCH-HOME <i>informed search subtask</i> INCREASE-ALTITUDE select [USE-EXHAUSTIVE-METHOD USE-DIRECT-METHOD].	<i>fly up to some altitude at which necessary surface detail is visible if orientation and position information has not been adequately maintained, perform an organized, exhaustive search maintaining an altitude at which the home marker can be seen else, move in the direction of the home marker and lower altitude when it becomes visible</i>
GOAL: MAINTAIN-ORIENTATION-INFO . OBSERVE-TOPOLOGY-ORGANIZATION.	<i>orientation gathered from topological information of the space and the organization of objects in it</i>
GOAL: MAINTAIN-POSITION-INFO . OBSERVE-TOPOLOGY-ORGANIZATION.	<i>position information incomplete because exact altitude is unknown; 2D position gathered from topological information of the space and the organization of objects in it</i>
GOAL: REACQUIRE-ORIENTATION INCREASE-ALTITUDE OBSERVE-TOPOLOGY-ORGANIZATION.	<i>if orientation is lost fly up to some altitude at which necessary surface detail is visible orientation gathered from topological information of the space and the organization of objects in it</i>
GOAL: REACQUIRE-POSITION INCREASE-ALTITUDE. OBSERVE-TOPOLOGY-ORGANIZATION.	<i>if position information is lost fly up to some altitude at which necessary surface detail is visible position information incomplete because exact altitude is unknown; 2D position gathered from topological information of the space and the organization of</i>
<i>objects in it</i>	

Reacquisition of position and orientation information was not performed regularly but when required, only a short vertical flight was necessary for successful reacquisition.

Automatic Breadcrumb Markers

A system of marking the space with a visual marker (a simple unmarked cube which we call a breadcrumb) was implemented. This mechanism can be used automatically, dropping markers at a constant frequency along the user's path. See figure 8.

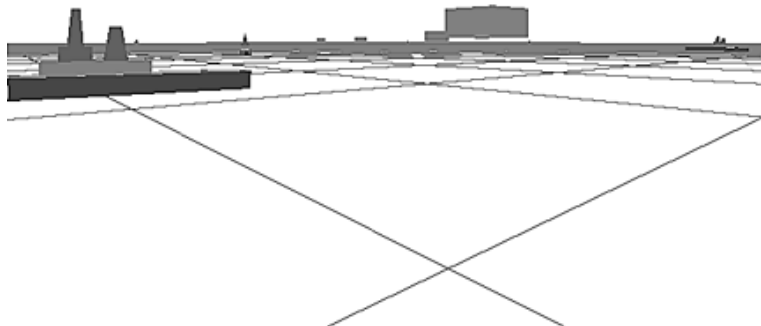


Figure 8: The breadcrumb tool

GOAL: ACQUIRE-ORIENTATION

```
.      select [  USE-MARKER-METHOD
.
.      USE-OBJECT-METHOD
.      USE-COMBINATION-METHOD ].
```

*if available, get directional
information from markers
else if available, get directional
information from objects
else if available, get directional
information from combinations of
markers and objects*

GOAL: ACQUIRE-POSITION

```
.      select [  USE-MARKER-METHOD
.
.      USE-OBJECT-METHOD
.      USE-COMBINATION-METHOD ].
```

*if available, get directional and
distance information from markers
else if available, get directional and
distance information from objects
else if available, get directional and
distance information from
combinations of markers and
objects*

GOAL: LEARN-SPACE

```
.      MARK-START
```

*learning subtask
move about the start location
leaving markers there to simplify
return*

GOAL: ACQUIRE-ORIENTATION

GOAL: ACQUIRE-POSITION

GOAL: MAINTAIN-ORIENTATION-INFO

GOAL: MAINTAIN-POSITION-INFO

```
MOVE.      general movement noting relative
```

*repeat throughout task performance
repeat throughout task performance*

*positions of objects and markers
attempting not to cross the trail*

GOAL: SEARCH-TARGET	<i>naive search subtask</i>
GOAL: MAINTAIN-ORIENTATION-INFO	<i>repeat throughout task performance</i>
GOAL: MAINTAIN-POSITION-INFO	<i>repeat throughout task performance</i>
. select [USE-EXHAUSTIVE-METHOD	<i>if space is not partitioned by the</i>
	<i>markers, perform an organized,</i>
	<i>exhaustive search using the markers</i>
	<i>to specify searched space</i>
. USE-PARTITION-METHOD].	<i>else, search partitioned areas</i>
	<i>systematically</i>
GOAL: SEARCH-HOME <i>informed search subtask</i>	
. select [USE-EXHAUSTIVE-METHOD	<i>if orientation and position</i>
	<i>information has not been adequately</i>
	<i>maintained (the space may be</i>
	<i>cluttered with markers), perform an</i>
	<i>organized, exhaustive search</i>
. USE-BREADCRUMB-METHOD].	<i>else, backtrack over the trail</i>
	<i>followed into the space by finding</i>
	<i>successive markers</i>
GOAL: MAINTAIN-ORIENTATION-INFO	
. PATTERN-ALIGNMENT.	<i>align viewpoint with directional</i>
	<i>configuration(s) of markers</i>
GOAL: MAINTAIN-POSITION-INFO	
. PARTITION-SPACE.	<i>partition space using directional</i>
	<i>configuration(s) or trails of markers</i>
GOAL: REACQUIRE-ORIENTATION	<i>if orientation is lost</i>
. MOVE-TO-FAMILIAR-LOCATION	<i>search for and move back to any</i>
	<i>directional configuration of markers</i>
. select [USE-MARKER-METHOD	<i>same as in</i>
	GOAL:ACQUIRE-ORIENTATION
. USE-OBJECT-METHOD	
. USE-COMBINATION-METHOD].	
GOAL: REACQUIRE-POSITION	<i>if position information is lost</i>
. MOVE-TO-FAMILIAR-LOCATION	<i>search for and move back to any</i>
	<i>directional configuration of markers</i>
. select [USE-MARKER-METHOD	<i>same as in</i>
	GOAL:ACQUIRE-POSITION
. USE-OBJECT-METHOD	
. USE-COMBINATION-METHOD].	

Reacquisition of position and orientation information was not performed regularly but when required, it demanded extensive time to relocate familiar space.

Manual Breadcrumb Markers

This mechanism can also be used manually, requiring the user to specify where markers should be dropped. See figure 8.

GOAL: ACQUIRE-ORIENTATION	<i>get directional information from</i>
. select [USE-MARKER-METHOD	<i>markers</i>
	<i>if available, get directional</i>
. USE-OBJECT-METHOD	<i>information from objects</i>
. USE-COMBINATION-METHOD].	<i>get directional information from</i>

GOAL: ACQUIRE-POSITION
 . select [USE-MARKER-METHOD

 USE-OBJECT-METHOD

 USE-COMBINATION-METHOD].

*combinations of markers and
 objects*

*get directional and distance
 information from markers
 if available, get directional and
 distance information from objects
 get directional and distance
 information from combinations of
 markers and objects*

GOAL: LEARN-SPACE
 . MARK-START

*learning subtask
 leave markers at the start location
 in a directional configuration*

GOAL: ACQUIRE-ORIENTATION
 GOAL: ACQUIRE-POSITION
 GOAL: MAINTAIN-ORIENTATION-INFO
 GOAL: MAINTAIN-POSITION-INFO
 select [MOVE

 select [USE-DISTANCE-METHOD
 USE-DEAD-RECKONING-METHOD
 USE-INTEREST-METHOD]].

*repeat throughout task performance
 repeat throughout task performance
 general movement noting relative
 positions of objects and markers
 markers dropped at regular distances
 markers dropped at turns
 markers dropped at points of
 interest*

GOAL: SEARCH-TARGET
 GOAL: MAINTAIN-ORIENTATION-INFO
 GOAL: MAINTAIN-POSITION-INFO
 select [USE-EXHAUSTIVE-METHOD

 USE-PARTITION-METHOD].

*naive search subtask
 repeat throughout task performance
 repeat throughout task performance
 if space is not partitioned by the
 markers, perform an organized,
 exhaustive search using the markers
 to specify searched space
 else, search partitioned areas
 systematically*

GOAL: SEARCH-HOME *informed search subtask*
 . select [USE-EXHAUSTIVE-METHOD

*if orientation and position
 information has not been adequately
 maintained (the space may be
 cluttered with markers), perform an
 organized, exhaustive search
 else, backtrack over the trail*

. USE-BREADCRUMB-METHOD
 followed into the space by finding
 successive markers (associated with
 DISTANCE-METHOD and
 DEAD-RECKONING-
 dropping markers)
 . USE-PARTITION-METHOD].
 systematically (associated with
 INTEREST-METHOD of

*USE-
 USE-
 METHOD for*

*else, search partitioned areas
 USE-
 dropping markers.*

GOAL: MAINTAIN-ORIENTATION-INFO
 . PATTERN-ALIGNMENT.

*align viewpoint with directional
 configuration(s) of markers*

GOAL: MAINTAIN-POSITION-INFO

. PARTITION-SPACE. GOAL: REACQUIRE-ORIENTATION . MOVE-TO-FAMILIAR-LOCATION . <i>directional configuration of markers</i> . select [USE-MARKER-METHOD . . USE-OBJECT-METHOD . USE-COMBINATION-METHOD].	<i>partition space using directional configuration(s) or trails of markers</i> <i>if orientation is lost search for and move back to any</i> <i>same as in GOAL:ACQUIRE-ORIENTATION</i>
GOAL: REACQUIRE-POSITION . MOVE-TO-FAMILIAR-LOCATION . <i>directional configuration of markers</i> . select [USE-MARKER-METHOD . . USE-OBJECT-METHOD . USE-COMBINATION-METHOD].	<i>if position information is lost search for and move back to any</i> <i>same as in GOAL:ACQUIRE-POSITION</i>

Reacquisition of position and orientation information was not performed regularly but when required, it demanded extensive time to relocate familiar space.

World Aligned Mapview

Mapview is a virtual map linked to the viewpoint. This map can be aligned with the world. This provides directional information and is similar to turning a map while locating a local turn-off of a roadway. An asterisk within a selection list designates a preferred method. See figure 9.

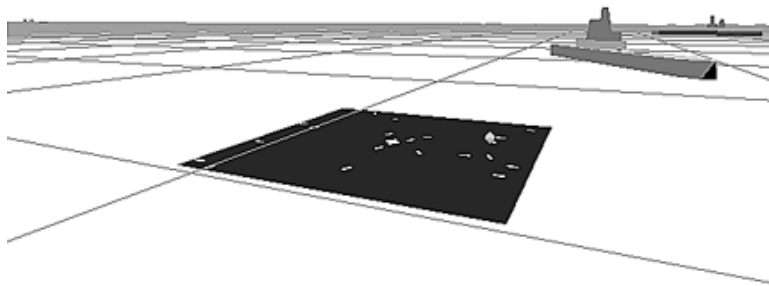


Figure 9: The world aligned mapview tool

GOAL: ACQUIRE-ORIENTATION . VIEW-MAP.	<i>map shows orientation directly</i>
GOAL: ACQUIRE-POSITION . VIEW-MAP.	<i>map shows position directly</i>
GOAL: LEARN-SPACE GOAL: ACQUIRE-ORIENTATION GOAL: ACQUIRE-POSITION	<i>learning subtask</i>

MOVE. *general movement within the space*
randomly looking between the map *and the*
world

GOAL: SEARCH-TARGET *naive search subtask*
 . select [USE-EXHAUSTIVE-METHOD *using the edges of the map as*
guidelines, search all parts of the *world*
 . USE-PARTITION-METHOD*]. *using configurations of objects in*
the space as separators, search
partitions separately

GOAL: SEARCH-HOME *informed search subtask*
 . USE-DIRECT-METHOD. *move in the direction of the home*
marker on the mapview tool until *the*
world view marker is visible

GOAL: MAINTAIN-ORIENTATION-INFO
 . VIEW-MAP. *map shows orientation directly*

GOAL: MAINTAIN-POSITION-INFO
 . VIEW-MAP. *map shows position directly*

GOAL: REACQUIRE-ORIENTATION
 VIEW-MAP. *if orientation is lost*
map shows orientation directly

GOAL: REACQUIRE-POSITION
 . VIEW-MAP. *if position information is lost*
map shows position directly

Reacquisition of position information was not performed at all since it was readily available. Orientation information required drawing a relationship between the map and the world and was not a demanding task.

View Aligned Mapview

The mapview can also be aligned with the viewpoint. The distinction between orientations is related to map organization and presentation methodologies described by Boff and Lincoln [2]. This method is similar to holding a map static while navigating long distances such as between cities. See figure 10.

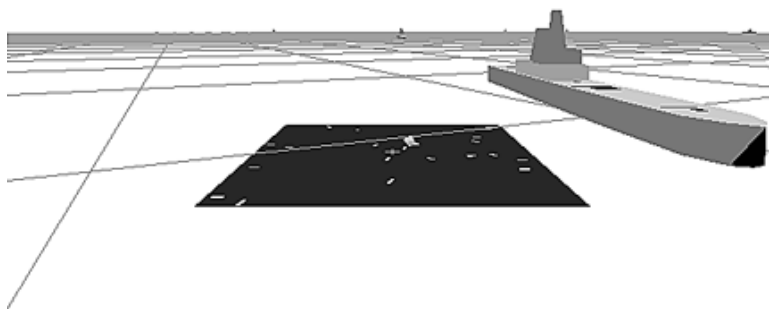


Figure 10: The view aligned mapview tool

GOAL: ACQUIRE-ORIENTATION

<ul style="list-style-type: none"> MOVE-VIEW-MAP. 	<i>small movements typically near an object on the map show correlation between map and world</i>
GOAL: ACQUIRE-POSITION <ul style="list-style-type: none"> VIEW-MAP. 	<i>map shows position directly</i>
GOAL: LEARN-SPACE <ul style="list-style-type: none"> GOAL: ACQUIRE-ORIENTATION GOAL: ACQUIRE-POSITION GOAL: MAINTAIN-ORIENTATION-INFO MOVE. 	<i>learning subtask</i> <i>repeat throughout task performance</i>
<i>general movement within the space randomly looking between the map world</i>	<i>and the</i>
GOAL: SEARCH-TARGET <ul style="list-style-type: none"> select [USE-EXHAUSTIVE-METHOD* <i>guidelines, search all parts of the</i> USE-PARTITION-METHOD]. <i>the space as separators, search partitions separately</i> 	<i>naive search subtask using the edges of the map as world using configurations of objects in</i>
GOAL: SEARCH-HOME <i>informed search subtask</i> <ul style="list-style-type: none"> USE-DIRECT-METHOD. 	<i>move in the direction of the home the</i>
<i>marker on the mapview tool until world view marker is visible</i>	
GOAL: MAINTAIN-ORIENTATION-INFO <ul style="list-style-type: none"> MOVE-VIEW-MAP. 	<i>small movements typically near an object on the map show correlation between map and world</i>
GOAL: MAINTAIN-POSITION-INFO <ul style="list-style-type: none"> VIEW-MAP. 	<i>map shows position directly</i>
GOAL: REACQUIRE-ORIENTATION <ul style="list-style-type: none"> MOVE-VIEW-MAP. 	<i>if orientation is lost small movements typically near an object on the map show correlation between map and world</i>
GOAL: REACQUIRE-POSITION <ul style="list-style-type: none"> VIEW-MAP. 	<i>if position information is lost map shows position directly</i>

Reacquisition of position information was not performed at all since it was readily available. Orientation information required drawing a relationship between the map and the world and often required movement. This is more time demanding than for the world aligned mapview.

Spatial Audio

A spatial audio cue, a steady positional tone generated using the Audio Cube, is used as an acoustic landmark. This is currently the only non-visual modality.

GOAL: ACQUIRE-ORIENTATION <ul style="list-style-type: none"> select [USE-GRID-METHOD <i>viewpoint to grid lines</i> USE-OBJECT-METHOD]. <i>information from objects</i> 	<i>align and confine movement of the</i> <i>if available, get directional</i>
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GOAL: ACQUIRE-POSITION

. select [USE-GRID-METHOD viewpoint to grid lines; requires lines . USE-OBJECT-METHOD]. distance information from objects	align and confine movement of the counting if available, get directional and
GOAL: LEARN-SPACE . GOAL: ACQUIRE-ORIENTATION . GOAL: ACQUIRE-POSITION GOAL: MAINTAIN-ORIENTATION-INFO GOAL: MAINTAIN-POSITION-INFO MOVE. general movement noting relative positions of objects and the landmark; typically random movement	learning subtask repeat throughout task performance repeat throughout task performance acoustic
GOAL: SEARCH-TARGET GOAL: MAINTAIN-ORIENTATION-INFO GOAL: MAINTAIN-POSITION-INFO USE-EXHAUSTIVE-METHOD.	naive search subtask repeat throughout task performance repeat throughout task performance perform an organized, exhaustive search
GOAL: SEARCH-HOME informed search subtask . SEARCH-SOUND within range of the acoustic . HOME-IN-ON-TARGET. its volume until within visual the target	randomly search the space until landmark move towards the sound increasing range of
GOAL: MAINTAIN-ORIENTATION-INFO . select [USE-GRID-METHOD viewpoint to grid lines . USE-OBJECT-METHOD]. information from objects	align and confine movement of the if available, get directional
GOAL: MAINTAIN-POSITION-INFO . select [USE-GRID-METHOD viewpoint to grid lines; requires lines . USE-OBJECT-METHOD]. distance information from objects	align and confine movement of the counting if available, get directional and
GOAL: REACQUIRE-ORIENTATION . MOVE-TO-FAMILIAR-LOCATION directional configuration of objects the GOAL:ACQUIRE- that the grid reacquired if lost . USE-OBJECT-METHOD].	if orientation is lost search for and move back to any used in POSITION; note method cannot be same as in GOAL:ACQUIRE-ORIENTATION
GOAL: REACQUIRE-POSITION . MOVE-TO-FAMILIAR-LOCATION directional configuration of objects the GOAL:ACQUIRE- . USE-OBJECT-METHOD].	if position information is lost search for and move back to any used in POSITION same as in GOAL:ACQUIRE-POSITION

Reacquisition of position information was performed regularly and was a complex task if the subject was outside the envelope of the sound source.

GENERAL CONCLUSIONS

The detail of the GOMS analysis brings out a number of artifacts which were previously unseen. In particular, parallelism between subtasks is revealed. Tasks which were performed in a primarily serial fashion are considered separable tasks whereas parallelism indicates that multiple subtasks are integrated [7]. Figure 11 is a PERT chart showing the general parallelism between subtasks. It can be viewed as a wider scope of figure 2. This is not the only parallelism in any treatment but is the only parallelism which can be generalized across all treatments (See Results section.). Note that all visual subtasks are dependent on orientation and position information for performance and that this information must be maintained while these subtasks are in progress. Because the focus of this study was on qualitative rather than quantitative measures, no timing information is provided on the PERT chart.

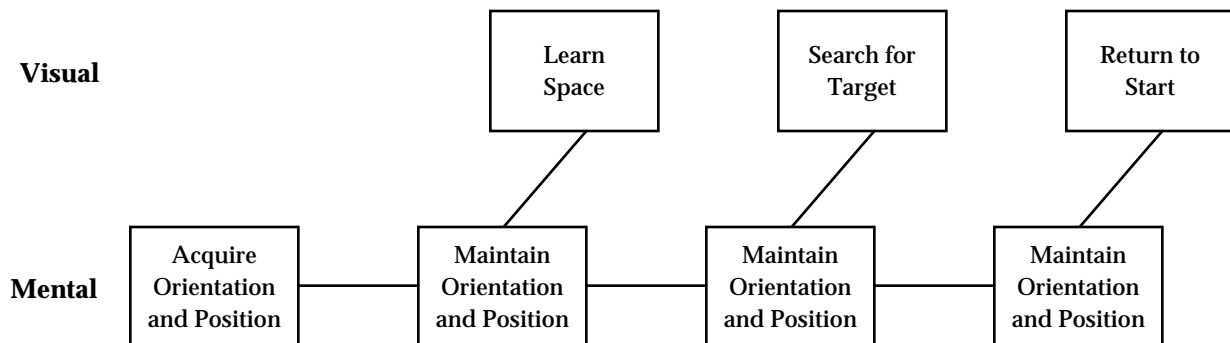


Figure 11: PERT chart of parallelism between subtasks

Another important issue is that for many treatments, reacquisition of information is rarely performed whereas for others, it is performed so often, it could almost be included as a part of the subtask. The GOMS analysis does not capture this information effectively. A note has been added after the GOMS analysis for each treatment describing information reacquisition. For example, using the coordinate tools, reacquisition of positional information was never done since it was readily available whereas reacquisition of orientation information was performed regularly because of the difficulties in its maintenance.

Tasks performed in virtual environments are far less structured than desktop-type tasks. It is difficult to make generalizations about behaviors since levels of performance between subjects can vary greatly even though they may have employed the same navigation strategy. For example, exhaustive searches are often more random than organized. Nevertheless, it is clear that the differences between the treatments was far greater than the differences between individual subjects indicating that the assertion that navigation cues and tools do in fact affect behaviors and strategies is valid.

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